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Regional Scale Meteorological Analysis and Prediction Using GPS Occultation and EOS Data

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The main objective of the research under this award is to improve regional meteorological analysis and prediction for traditionally data limited regions, particularly over the Southern Ocean and Antarctica, using the remote sensing observations from current and upcoming GPS radio occultation missions and the EOS instrument suite. The major components of this project are:

- Develop and improve the methods for retrieving temperature, moisture, and pressure profiles from GPS radio occultation data and EOS radiometer data.
- Develop and improve a regional scale data assimilation system (MM5 4DVAR).
- Perform case studies involving data analysis and numerical modeling to investigate the impact of different data for regional meteorological analysis and the importance of data assimilation for regional meteorological simulation over the Antarctic region.
- Apply the findings and improvements from the above studies to weather forecasting experiments.
- In the third year of the award we made significant progress toward the remaining goals of the project. The work included carefully evaluating the performance of an atmospheric mesoscale model, the Polar MM5 in Antarctic applications and improving the upper boundary condition.

1. Atmospheric Occultation Profile Retrieval (OSU/CEEGS)

With the goal of obtaining improved products that can be applied towards initializing and verifying regional models, we have conducted investigations to better understand the GPS occultation retrieval algorithms and their associated error budgets. The use of various high-level occultation data products should be able to improve atmospheric pressure fields over Antarctica, where large gaps exist in the in-situ observing network. In particular, we have examined and compared data products from data centers including GFZ, UCAR COSMIC and JPL GENESIS projects. In essence, we implemented our own retrieval algorithm with objectives including comparison with data products available from other data centers, e.g., UCAR COSMIC project. The inability of GPS signal penetration through the lower troposphere is still a challenge, both in algorithm and hardware technology because of the rapid change of the moisture content, lower troposphere inhomogeneities, and multipath problem, etc. In addition to using basic geometric optical methods, we also attempted to incorporate algorithms to mitigate multipath effects associated with the lower troposphere. Methods such as back propagation methods, canonical transform and full spectrum inversion have been studied.

Figure 1 shows an example retrieval of temperature profiles compared with other data products: GFZ (<http://champ.gfz-potsdam.edu>), UCAR (<http://www.cosmic.ucar.edu>), and JPL (<http://genesis.jpl.nasa.gov>) for CHAMP occultation #117 on May 21, 2001. The data products show good agreement. It is also evident, however, that the lowest few km's of retrieval still show discrepancy. The CHAMP data appear to be able to penetrate lower into the troposphere for this particular comparison.

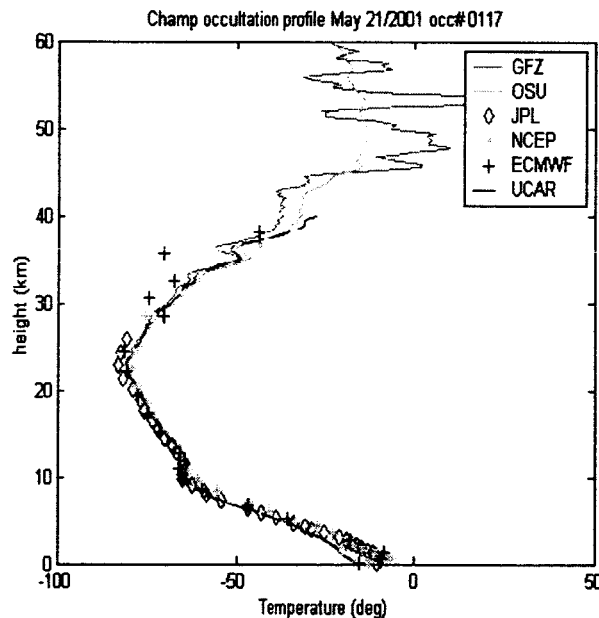


Figure 1. CHAMP Profile over Antarctica.

Occultation Profile Distribution and Penetration

GPS occultation has the potential to improve the meteorological analyses and forecasts, including those of atmospheric pressure fields. Figure 2 shows the geographic coverage of three different measurement techniques (CHALLENGING Minisatellite Payload [CHAMP] occultation Jan-Mar, 2003, Automatic Weather Stations and Radiosondes). GPS occultation has greater geographical coverage, while the other two techniques provide dense time series but at fixed locations.

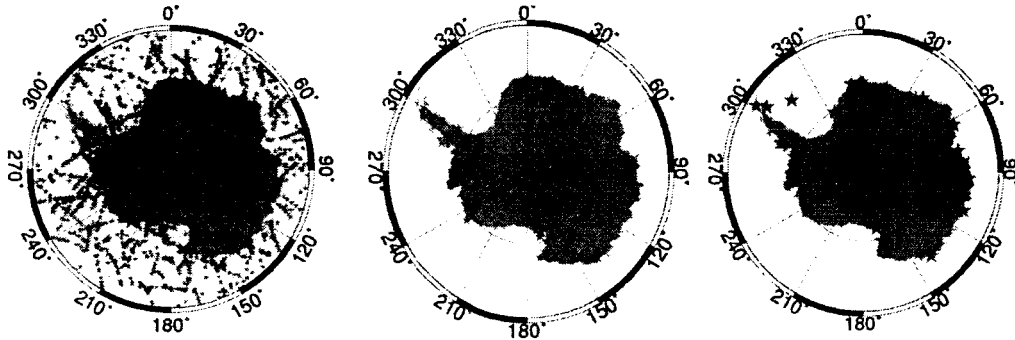


Figure 2. Comparison map for (a) CHAMP occultation, (b) Automatic Weather Stations and (c) Radiosondes in Antarctica.

Figure 3 illustrates the distribution of CHAMP occultation penetration over three different regions. In the tropical region (defined here as 30°N-30°S), which is warm and moist, only about 10% signals penetrate down to 1 km above the MSL (Fig. 3b). Rapidly changing moist features in the lower atmosphere also affect signal tracking.

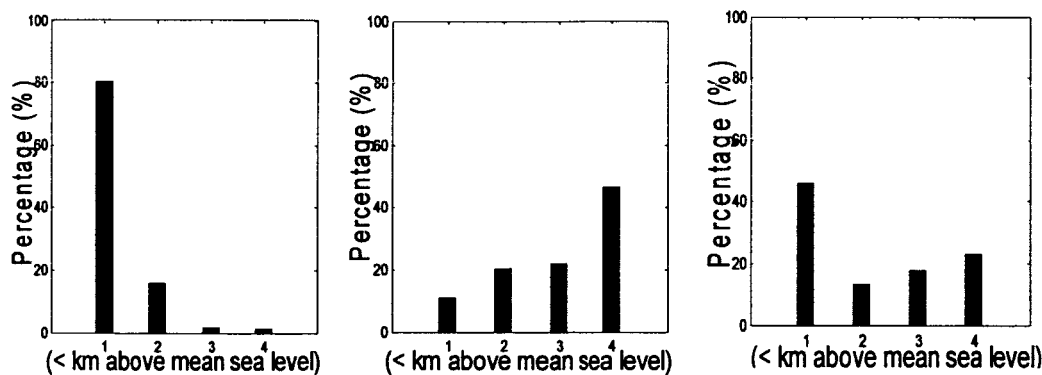


Figure 3. Histograms of CHAMP occultation penetration depth (referring to the MSL) over the Arctic (80% signal penetration to below 1 km), tropical (10%) and Antarctic (50%) regions. CHAMP occultation data are from Jan-March, 2003.

CHAMP occultation performs much better in Arctic region, which is cold and over relatively dry ocean regions. Figure 3a shows that nearly 80% of the profiles reach to within 1 km above the MSL. Figure 3c shows that over Antarctica, which has a relatively high surface elevation, nearly 50% of the profiles reach to within 1 km of mean sea level. After removing the

topographic effect (i.e., referencing the occultation profiles to the ECMWF topography), Ge and Shum (2003) show that Antarctic signal penetration is similar that of the Arctic region (~80% signals penetrate to within 1 km above the Earth's surface). Thus, the potential for forecast improvement is particularly large over Antarctica as the signal penetration is strong in a region of otherwise limited data coverage.

Figure 4 shows the zonal and meridional distribution of CHAMP profiles. Due to the orbital configuration of the GPS satellite, there are more occultation events in the middle latitudes than in the tropical and polar regions. Meridional distribution is more uniform.

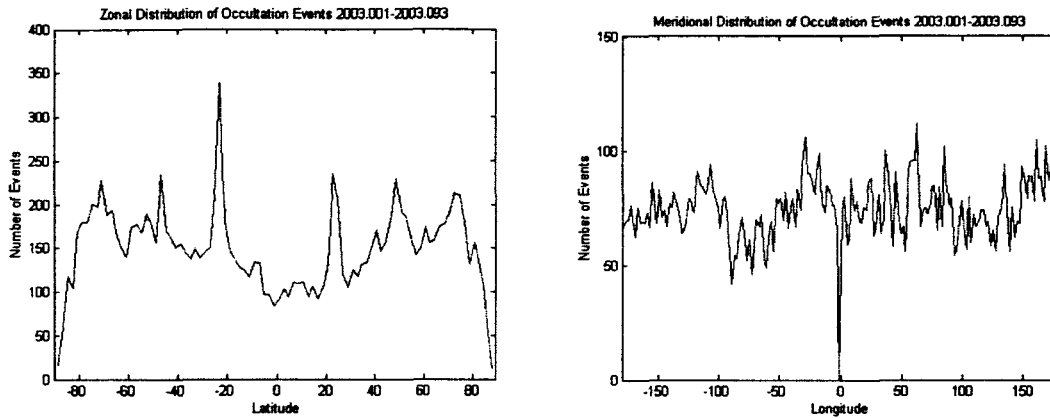


Figure 4. Zonal and meridional distribution of CHAMP occultations (2003.001-093)

Figure 5 shows the results over Antarctica, where nearly 50% of the profiles reach within 1 km of mean sea level. Signal penetration over Antarctica would improve if the topographic effects could be accounted for, and the occultation profiles could be properly referenced to the "true" Earth surface.

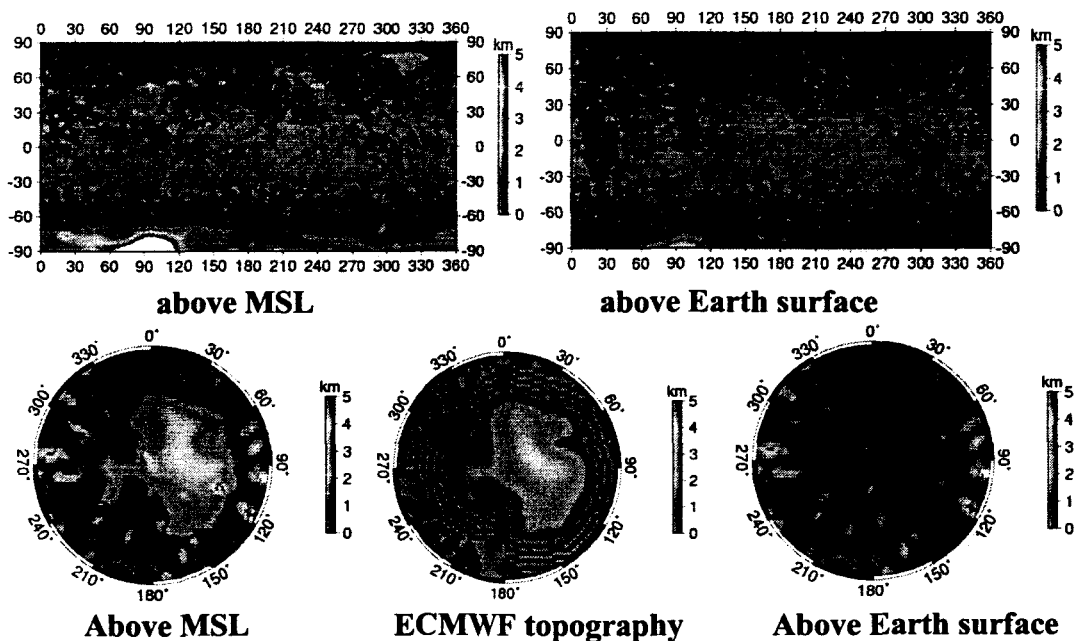


Figure 5. Lowest penetration altitude above different surfaces

Comparison of GPS Derived Pressure with ECMWF, NCEP and Radiosonde data

We compare three months of pressure profiles available from CHAMP occultation, with ECMWF, NCEP and radiosonde datasets to evaluate the relative performance of each dataset. From the analysis (Fig. 6), we found that there exists a positive bias in CHAMP derived pressure (CHAMP measures larger pressure values) compared to the other datasets. The bias is larger for the South Pole region than for any other region. The root mean square (RMS) difference between

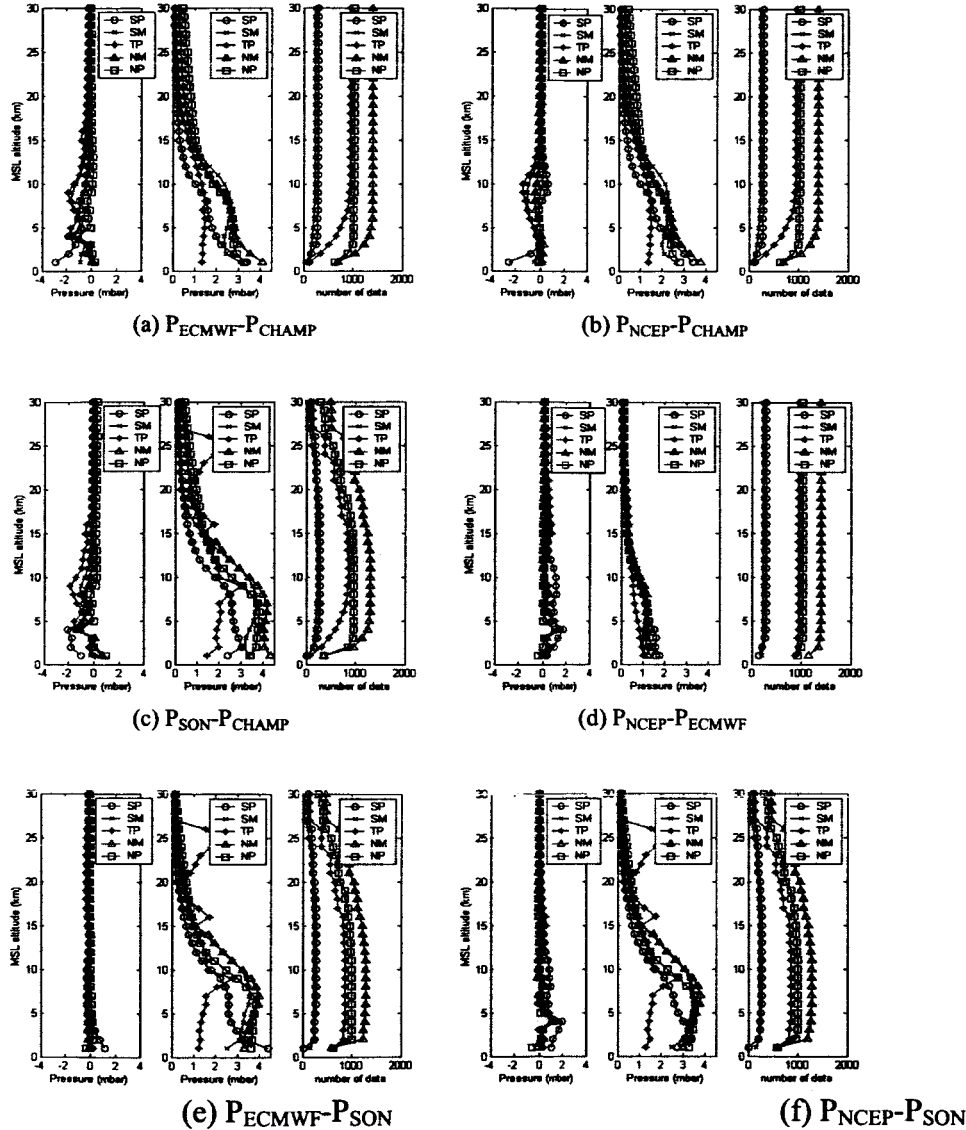


Figure 6. Inter-comparison (Pressure difference) of CHAMP-derived pressure profiles (P_{CHAMP}), ECMWF pressure profile (P_{ECMWF}), NCEP pressure profile (P_{NCEP}) and radiosonde pressure profile (P_{SON}). In the figures: SP—southern polar region (60-90°S), SM—southern mid-latitude region (30-60°S), TP—tropical region (30°S-30°N), NM—northern mid-latitude region (30-60°N), NP—northern polar region (60-90°N). For each figure: left panel—mean of pressure difference, middle panel—standard deviation of pressure difference, right panel—number of values in each level used for the comparison.

CHAMP pressure and other data sets is as large as 4 hPa globally at 1 km above MSL. Larger differences are expected at the surface. It is surprising that the best comparison occurs in the tropical region. Usually in the tropics, water vapor degrades the occultation results the most. The comparison of ECMWF and NCEP shows better agreement than any other comparisons, both in bias and RMS. This reflects a certain degree of consistency between the two models. The South Pole region, however, is still the area with the biggest discrepancy. This once again confirms our conclusion that models perform poorly in this area. Radiosonde, as an independent measurement technique, provides another alternative to evaluate the data. Through the comparison of CHAMP pressure with radiosonde pressure, we suspect that CHAMP pressure is positive biased. Biases or errors exist in one or both measurements. Poor temporal and spatial sampling could contribute to the differences. Meanwhile, the radiosonde data does not agree well with the models (NCEP and ECMWF) in data sparse (SP) regions.

1-Dimension Variation (1DVAR) Retrieval

We investigated the possibility of combining information contained in the measurements (GPS occultation) with the prior data (NWP models) in a statistically optimal way using a 1DVAR approach. In our processing, the state vector contains 33 elements:

- 16 temperature values on fixed pressure levels
- 16 ln(specific humidity) on fixed pressure levels
- 1 surface pressure element.

Background information is taken from ECMWF analysis.

Observation is GPS-occultation derived refractivity.

The background covariance matrix is diagonal for this experiment only, and we will adopt a full matrix if available. The observation error matrix is formed as follows:

- Percentage error in refractivity is 1% at the surface and falls linearly to 0.2% at the height of 10 km. Above 10 km, the error remains 0.2% to 35 km altitude
- The correlations are assumed to have an exponential decay with the separation in geopotential height, given by:

$$E_{nm} = \sigma_n \sigma_m \exp(-l(z_n - z_m)) \quad l = 3 \times 10^{-4} m^{-1}$$

From the 1DVAR result (Fig. 7), we find that the temperature error in the 200-300 hPa region is reduced up to ~80%–90%. Measurements contain significant surface pressure information, especially in the tropical region. Surface pressure enters the equation through hydrostatic equation on every level. If the system (observation or background) is biased, the bias would enter the surface pressure value. Information is not substantially degraded if the occultation does not reach the surface. Standard deviation of surface pressure is reduced by 50% - 60% of the original value (2.5 hPa).

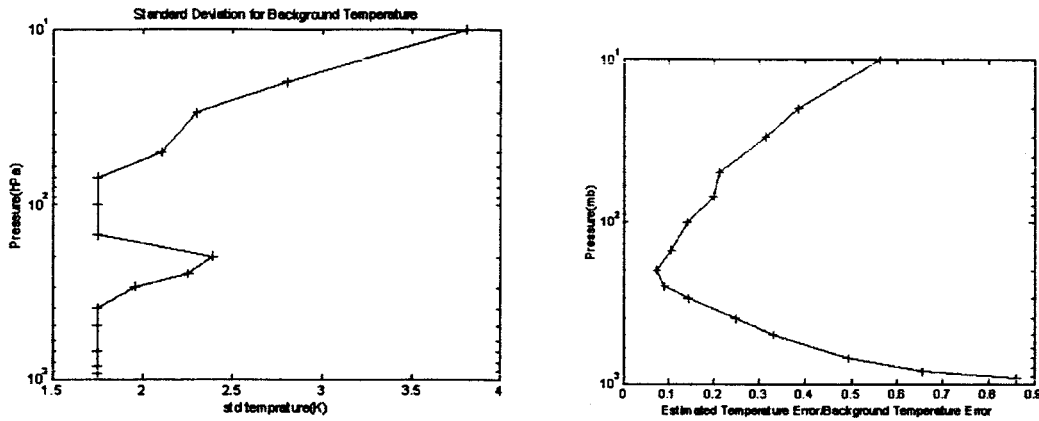


Figure 7. 1DVAR Result

Validation of CHAMP and SAC-C pressure profiles

We analyze the one month occultation-derived pressure climatology pattern and pressure-model difference between CHAMP and SAC-C processed by UCAR and JPL data centers (Fig. 8). The results show inconsistency between centers and between satellites. At 10 km altitude, there is no multipath and water vapor ambiguity problem, but the pressure difference sometimes exceeds 5 hPa. UCAR's result indicates large discrepancy with NCEP for the Antarctic region. JPL's SAC-C pressure fields show large equatorial difference when compared with models. The reason for these differences is unknown at present. All the profiles used in this study have passed quality control. Profiles in the pressure anomaly regions need to be carefully examined.

When comparing every single profile by different centers, one finds that the data products usually do not match perfectly. The causes for data product discrepancies include different retrieval algorithms and/or different approximations adopted in the processing procedures. We have conducted evaluations of these procedures and approximations and their sensitivity to the pressure retrieval towards understanding the causes for the processing discrepancy. In particular and for example, it is found that definitions or approximations of geopotential and height are inconsistent.

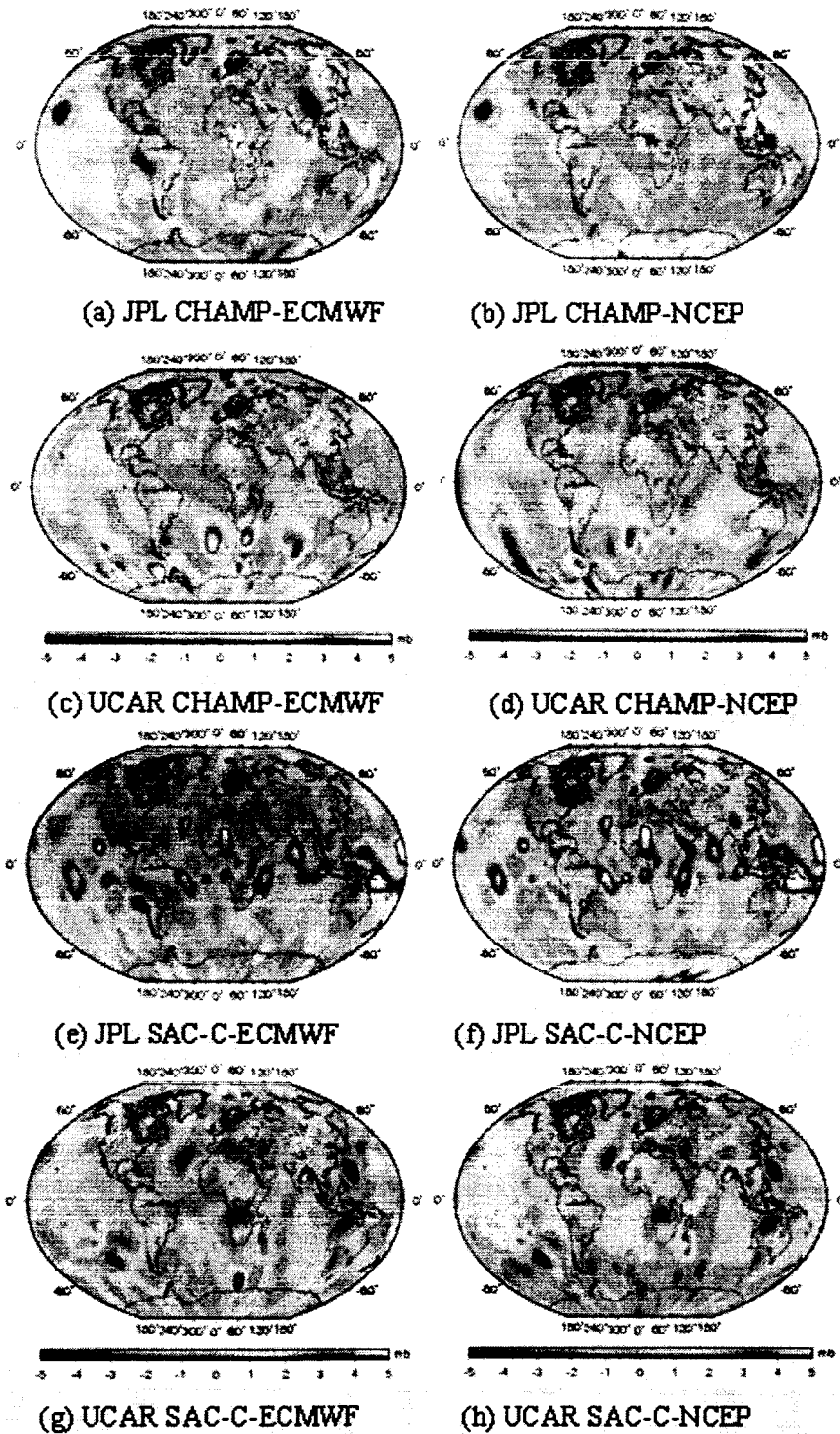


Figure 8: Pressure difference of GPS occultation profile with weather analysis models at 10 km altitude. (Derived by $10^\circ \times 10^\circ$ block mean)

2. Model Verification (OSU/BPRC)

Polar MM5

The atmospheric model used in this study is the Polar MM5 that was developed by the Polar Meteorology Group of the Byrd Polar Research Center. It is a version of the Fifth Generation Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5) specifically adapted for the polar regions (Bromwich et al. 2001). The ice nuclei concentration equation (Meyers et al. 1992) is implemented in the explicit microphysics parameterization. The cloud ice and water content predicted by the microphysics parameterization are used to determine the radiative properties of clouds in the NCAR Community Climate Model, Version 2 (CCM2) radiation parameterization. Two additional substrate levels (which increase the substrate depth to 1.91 m, compared to the 0.47 m in the unmodified version) are added to the multi-layer soil model proposed by Dudhia (1996). Furthermore, a variable fraction sea ice cover was added as to the land surface types. The ETA boundary layer scheme has been used for all simulations with the Polar MM5 because several studies (Bromwich et al. 2001; Cassano et al. 2001) have shown that it is the best boundary layer scheme for the polar regions available via the MM5 modeling system.

Model Evaluation

Polar MM5 has been applied to several synoptic case studies and climate scenarios. Furthermore, it is applied daily to support the forecasting needs of the United States Antarctic Program at McMurdo, Antarctica through the Antarctic Mesoscale Prediction System (AMPS, Bromwich et al. 2003). A model evaluation here helps identify those features of Polar MM5 that we intend to improve upon by consideration of the GPS data. As a case study, the performance of AMPS is evaluated for its ability to forecast mesoscale cyclogenesis in the western Ross Sea during 13-17 January 2001. Observations during that test period indicate the presence of a complex trough having two primary mesoscale lows that merge to the east of Ross Island shortly after 0700 UTC 15 January. In contrast, AMPS predicts one primary mesoscale low throughout the event, incorrectly placing it until the 1800 UTC 15 January forecast, when the observed system carries a prominent signature in the initialization. The model reproduces the evolution of upper-level conditions in agreement with the observations, and shows skill in resolving many small-scale surface features common to the region (i.e., katabatic winds; lows and highs induced by wind/topography). The AMPS forecasts can rely heavily on the representation of surface lows and upper level forcing in the first-guess fields derived from NCEP's AVN model. Furthermore, even with relatively high spatial resolution, mesoscale models face observation-related limitations on performance that can be particularly acute in Antarctica. This emphasizes the need for the enhanced atmospheric database that can be provided by GPS Occultation.

Another evaluation of the AMPS system was performed for the two-year period between September 2001 through August 2003 (Bromwich et al. 2004b). The modeling system consists of several domains ranging in horizontal resolution from 90 km covering a large part of the Southern Hemisphere, to 3.3 km over the complex terrain surrounding McMurdo. The simulated 12-36 h surface pressure and near-surface temperature at most sites have correlations greater than 0.95 and 0.75, respectively, and small biases. Surface wind speeds reflect the complex topography and generally have correlations between 0.5-0.6, and positive biases of 1-2 m s⁻¹. In

the free atmosphere, $r > 0.95$ (geopotential height), $r > 0.9$ (temperature), and $r > 0.8$ (wind speed) at most sites. Over the annual cycle, there is little interseasonal variation in skill. Over the length of the forecast, a gradual and nearly linear decrease in skill is observed from hour 0-72. An exception to this is for the surface pressure, which improves slightly in the first few hours from the initial condition, due in part to the model adjusting from the surface pressure biases in the initial conditions that are caused by the initialization technique over the high, cold terrain. Therefore, it is again imperative that we seek improvements to the model initialization.

3. Improvements to the MM5 4DVAR System (UCAR)

The initialization of MM5 can be enhanced by the incorporation of GPS occultation through the four-dimensional variational analysis (4DVAR) system, with care taken to limit the errors associated with inertia-gravity waves. It is well known that inertia-gravity waves can be excited by dynamical imbalances in the initial conditions of a numerical model. These gravity waves can cause significant pressure oscillations, especially in the early stages of a forecast. Also, the insertion of observations (through a data assimilation system) can also cause dynamic imbalances (between wind and mass fields) and generate gravity waves. The purpose of 4DVAR is to obtain an optimal fit between observations and the model solution within the assimilation window. If these gravity waves are not filtered, the 4DVAR can attempt to fit observations to transient model gravity waves, and reduce the overall effectiveness of the assimilation system. Therefore, reducing imbalances in the model initial condition or in a data assimilation procedure is an important topic for numerical weather prediction and data assimilation.

A case study is performed using the improved MM5 4DVAR system. Various types of observations have been collected, screened, and assimilated in an augmented MM5 4DVAR for an intense synoptic storm case in the Ross Sea that shut down McMurdo base for 7 days during December 2001 (Monaghan et al. 2005; study done by OSU/BPRC). Because AMPS made poor forecasts during the second half of the storm period, a detailed assimilation study on the case was carried out as an effort to identify potential problems with AMPS. The experiments have focused on the impact assessment of GPS Radio Occultation (RO) data while other observations are included to maintain the quality of the analysis for an extended period of assimilation. The observations other than GPS RO data appeared to be critical to prevent the assimilation system from exaggerating the potential impact of GPS RO data. The assimilation experiments were aimed at investigating the impact of real GPS RO data under an experimental set-up close to AMPS and providing practical guidance on the future applications in AMPS-3DVAR, which includes the development of advanced observation operators for GPS RO as well.

Collection of Observations

GPS RO measurements from CHAMP and SAC-C (Satellite de Aplicaciones Cientificas-C) missions were collected and then processed with inversion algorithm of COSMIC Data Analysis and Archive Center (CDAAC) at UCAR (Fig. 9). Following is the list of observations, other than GPS RO data, collected and assimilated: TEMP (rawinsonde and pibal), SYNOP (surface, ship, drifting buoy, and PAOB), aircraft observations (AIREP, PIREP, and AIRCAR), ATOVS retrieved soundings from NESDIS (NOAA 15 and 16), MODIS/Terra retrieved soundings, satellite motion vectors, SSM/I retrievals (rainfall rate, total liquid water, precipitable water vapor, and surface wind speed) from DMSP 13-15, and QuikSCAT surface wind vectors.

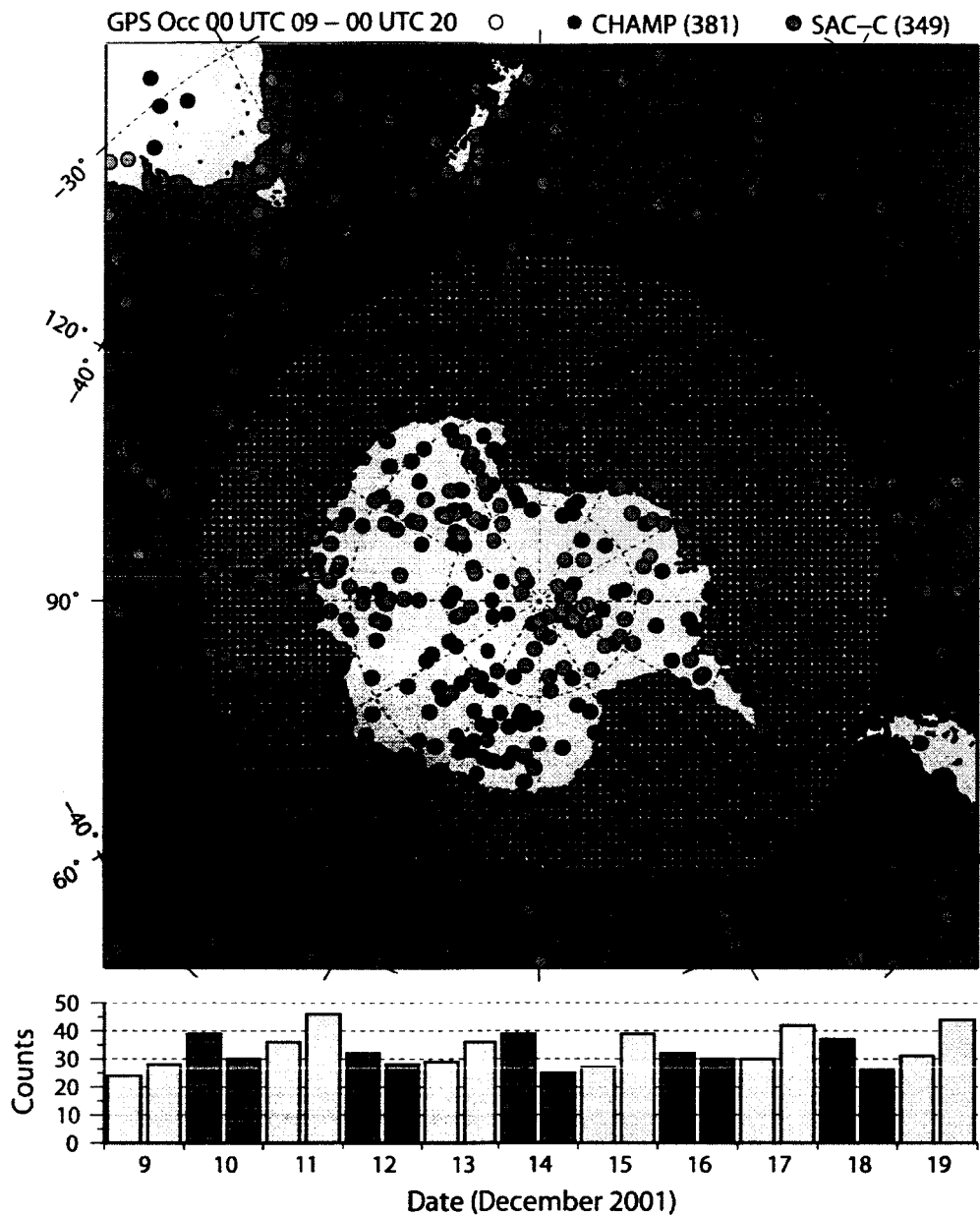


Figure 9. Distribution of CHAMP (filled red circles) and SAC-C (filled green circles) GPS Radio Occultation soundings. The area enclosed with yellow plus (+) marks including Antarctic continent denotes verification domain. Histogram represents the number of soundings per 12-h in the assimilation model domain.

Screening of Observations

In order to exclude some uncertainties not directly related to GPS RO data and to evaluate the impact of GPS RO data more precisely in a well-defined environment, the assimilation experiments were run in an off-line mode. The approach was motivated from recognition of a big systematic difference between NCEP and ECMWF analyses over the Antarctic area, manifested while estimating the error of the background field with the NMC-

method. It is obvious that a biased background field leads to a biased analysis especially in data-sparse areas and the only way to account for bias in the background field is to do so explicitly, by correcting the bias of the background field prior to assimilation. Since the mean difference does not indicate which is better, however, 50% of the perceived mean bias was removed from the background field (NCEP analysis) assuming the same accuracy in the two analyses. Fairly intensive testing demonstrated that the approach helps assimilation be more effective by better assuring the background field is unbiased. Similarly an "intelligent" off-line algorithm has been devised to perform a series of data processing tasks including: decoding, quality check, identification and assignment of observational error (in case a good reference is absent), removal of potential bias, and temporal/spatial data thinning (in case the observations have a higher resolution than the assimilation model). All data have been collected for a two-month period centered on the storm event to estimate long-term observation errors. The purpose of the off-line processing (in addition to a built-in quality control inside the assimilation model) is, of course, to avoid adverse influences from bad data.

Assimilation Results

An Observing System Experiment, parallel runs with and without GPS RO data, was run for 8 days. Different initial times were taken every 12-h during the 8-day period, and continuous assimilations with a window size of 12-h were performed up to 48 hours (i.e., 4 cycles). Prior to ingesting all available data, a simple data denial experiment on GPS RO has been conducted with only GPS RO data and rawinsonde measurements. The experiment showed a remarkable positive impact of GPS RO data, but the quality of analyses was continuously degraded with analysis cycling. The experiment has confirmed the good quality of GPS RO data as well as the necessity of other data to maintain the quality of analysis in the cycling.

When all available data were assimilated, the contribution of GPS RO data to observational cost function was about 3 % on average (Fig. 10). The results for first 12-h assimilations (1st cycle), averaged over all cases, revealed a noticeable error reduction in temperature at lower stratospheric levels, which demonstrates GPS RO data are valuable in better characterizing the tropopause (Fig. 11). Despite the forecast errors having been reduced to some degree, especially at upper levels, the impact of GPS RO data for the 1st cycle was marginally positive or near neutral. Another remarkable feature was the large case-to-case variation. A detailed examination exposed that the forecast impact is strongly dependent on the location of GPS RO relative to the synoptic situation. As more soundings hit dynamically sensitive areas (which leads to significant error reduction in the forecasts), a bigger impact tends to result. Since the horizontal observational density from current GPS RO missions (CHAMP and SAC-C) is still low, an immediate and large positive impact in the analysis was barely observed.

Significant positive impact of GPS RO data has been obtained by continuing the assimilation up to 48 hours (Figs. 12 and 13). The assimilation of GPS RO data for an extended period improved all parameters in all forecast ranges, and the positive impact of GPS RO data increased persistently with the lengthened analysis period. It is concluded that the positive impact of GPS RO data could be seen even under an operational environment as the analysis errors were kept to a degree comparable to those in the cold start runs throughout the cycling period. A significant error reduction was noted over the interior of Antarctica when the forecasts were verified against observed GPS RO data.

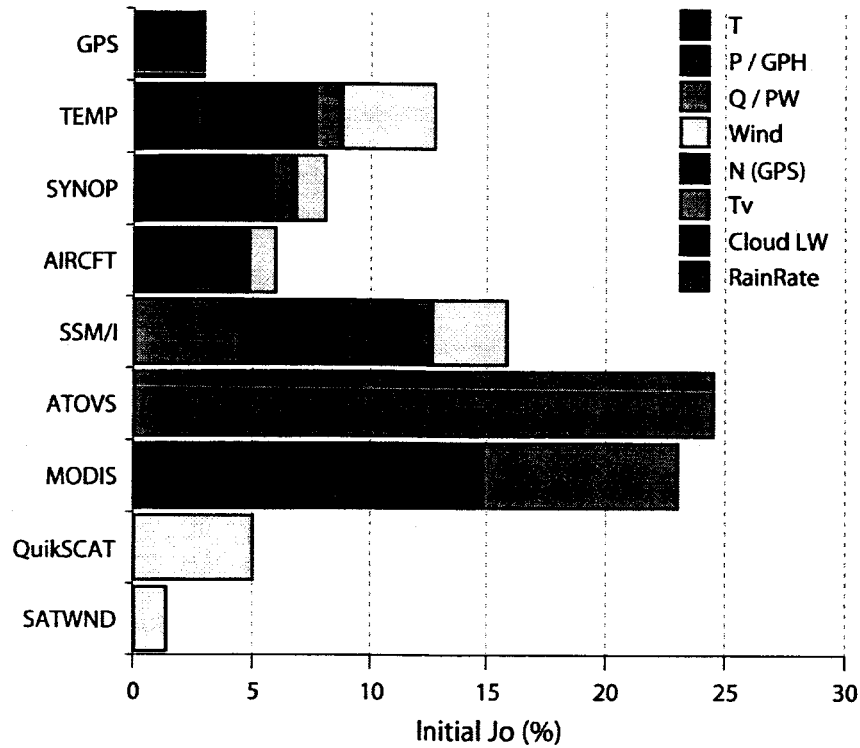


Figure 10. Contribution of each observation type to observational cost function before assimilations, averaged over all cases.

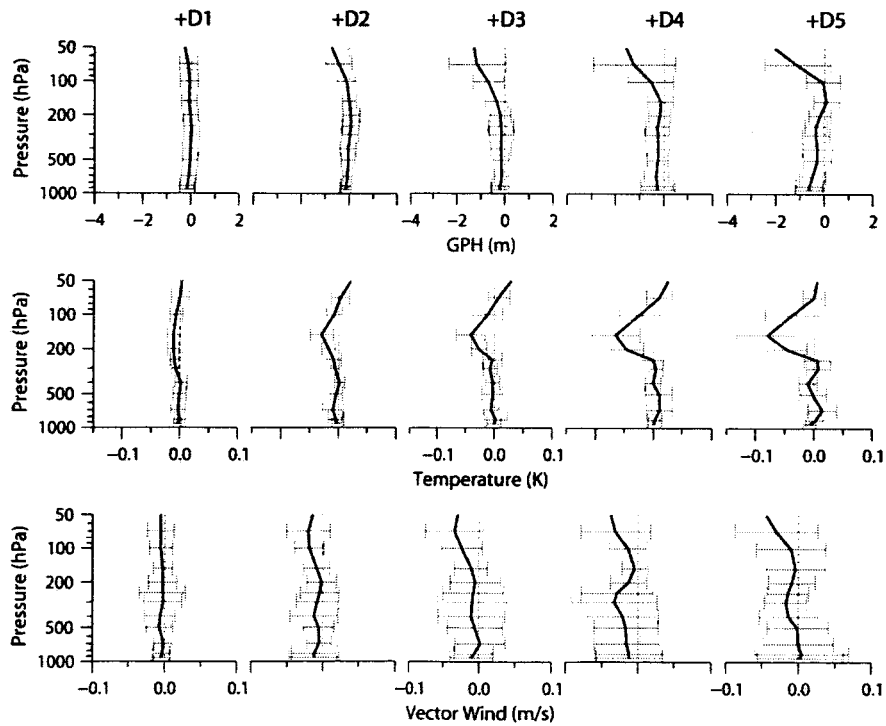


Figure 11. Difference of r.m.s. forecast errors, which is GPS run - No GPS run and averaged over all cases in first cycles. Horizontal bar denotes case-to-case variations.

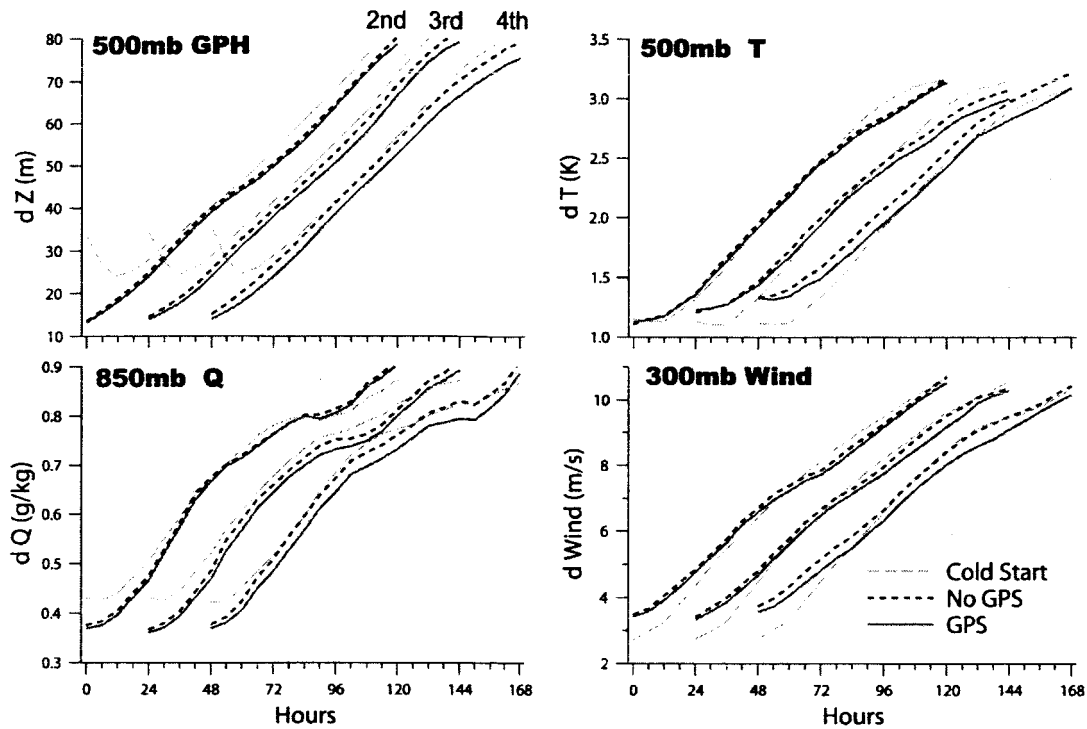


Figure 12. Root mean square errors, against ECMWF analyses, with forecast time. Cold start is initialized with NCEP AVN analyses at the end of assimilation period for each cycle.

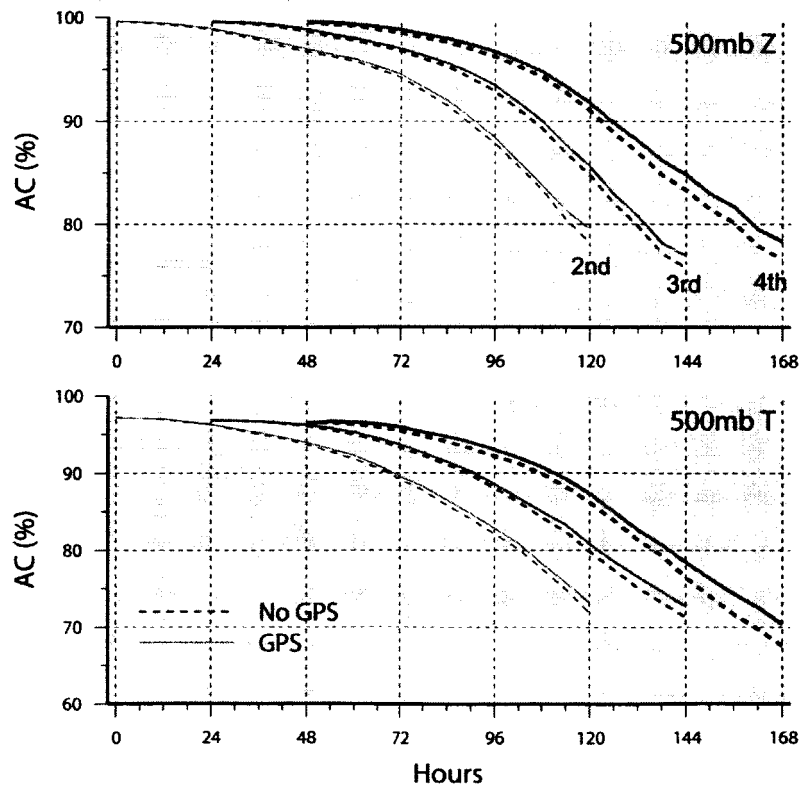


Figure 13. Anomaly correlation coefficients against ECMWF analyses. The climatology used is a 30-yr average (1972-2001) taken from ERA-40.

The diagnostics to investigate the impact of GPS RO data on the storm development indicated that GPS RO data are especially helpful to detect the upper level precursors for storm development (e.g., intensification of troughs and ridges; enhancement of baroclinicity due to the increase of thermal gradient). The changes in mass field also accompanied corresponding changes in wind fields such as strengthened jet streams and dislocated center for jet streaks. Although the difference between the parallel runs was very small in the short forecast ranges, the subtle changes in the analysis and subsequent non-linear evolution of the perturbation lead to noticeable forecast differences at longer ranges (Fig. 14).

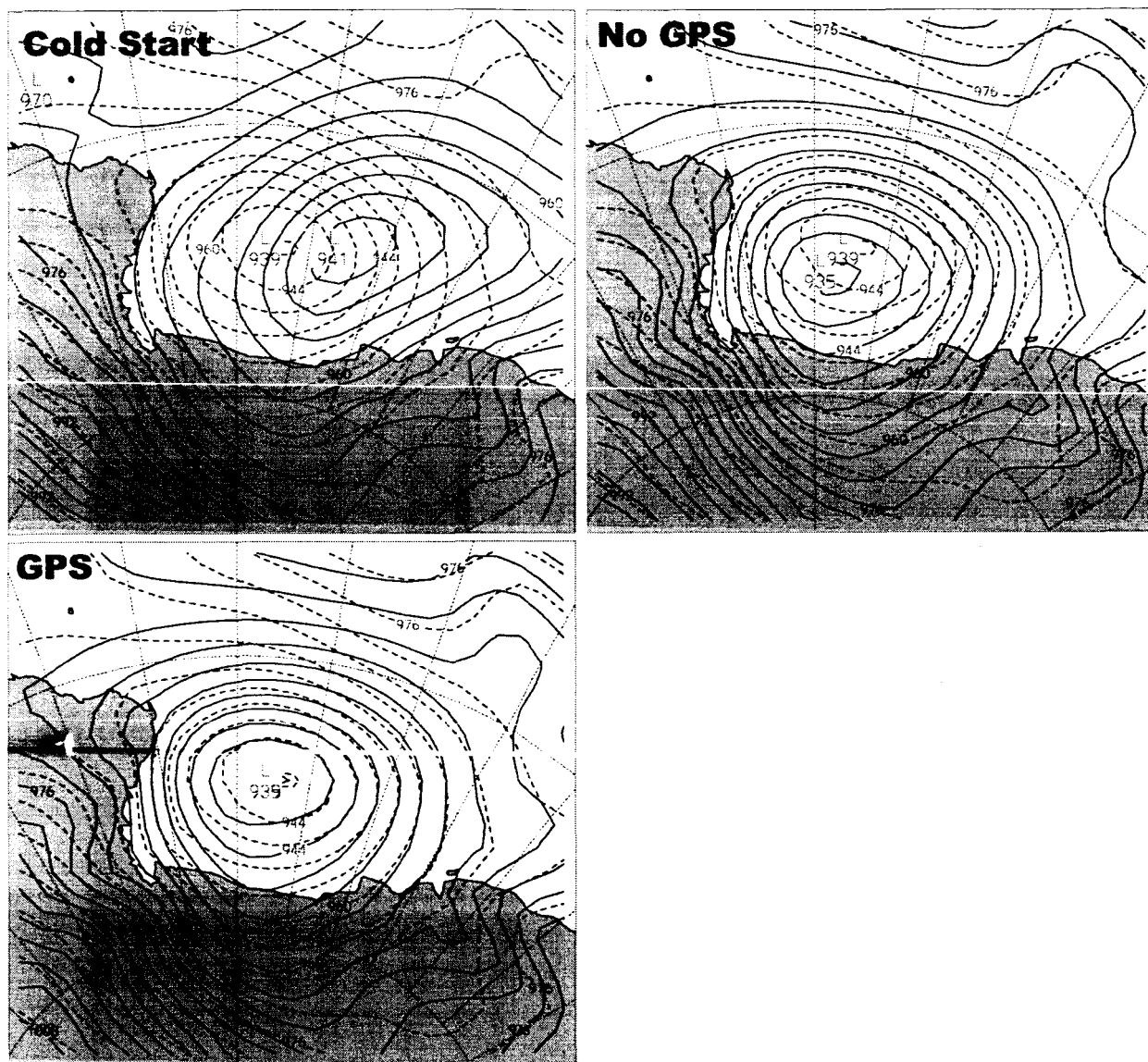


Figure 14. 66-hr forecast of mean sea level pressure (solid contour) valid at 0600 UTC 14 December 2001. ECMWF analysis valid at the same time (dashed contour) is overlaid as a reference.

4. Upper Boundary Condition (OSU/BPRC)

An improvement to the Polar MM5 system for Antarctica has also been considered. We have investigated the impact of the upper boundary condition on the Polar MM5 simulations. In simulations over the Antarctic domain, severe wave reflection is found at the model top with the standard MM5 radiative upper boundary condition of Klemp and Durran (1983). This scheme has been used successfully in many parts of the world. It was, however, originally developed for relatively flat areas where waves are not strong enough to propagate to the model top. Those assumptions and equations are not valid for Antarctica, where strong waves are generated by the steep terrain. The scheme was derived for pure hydrostatic gravity waves without the consideration of Coriolis forcing. The assumptions used in this upper boundary condition are probably not valid over Antarctica.

Compared with GPS/MET data, the temperature bias with the standard scheme can be as large as 20°C at the model top (Wei et al. 2004). Furthermore, the simulated upper level jet is too weak. Wave reflections impact not only upper levels but also surface fields. The bias in sea level pressure is as large as 20 hPa. Another contributor to the large biases generated by the radiative upper boundary condition is the conflict between the basic requirement of sigma coordinates ($\sigma=0$ at model top) and the fact that σ is not equal to zero for the radiative boundary condition. This conflict is amplified over a steep terrain area such as Antarctica.

Considering the flaw of the current radiative upper boundary condition in MM5, we experimented by raising the model top pressure level from 100 hPa to 10 hPa to increase the wave dissipation during vertical propagation (Wei et al. 2004). This does reduce the magnitude of the errors, but wave reflections and biases still occur. Furthermore, raising the model top must be considered a last resort because of added computational cost. Moreover, when the model top is set within the stratosphere, the model performance will likely become worse because some physical parameterizations, the radiation schemes and ozone effects in particular, are poorly validated due to the lack of observed data. Vertical resolution may also be too poor to accurately locate the tropopause. These factors cause unnecessary complexity.

Increasing the absorbing factor is potentially a promising approach to solve the upper boundary condition problem over the Antarctic. However, as implied by the results of Morse (1973), increased filtering cannot be applied abruptly at some selected distance from the boundary because erroneous reflection back into the model domain can occur. As Pielke (1984) pointed out, both insufficient and excessive damping in the absorbing layer can cause wave reflection. In addition, the depth of an absorbing layer must be greater than the vertical wavelength of the mesoscale disturbance for the scheme to be effective.

A new nudging upper boundary condition has been designed, tested, and implemented by Wei et al. (2004). In the new scheme, the simulation is nudged toward a specified large-scale analysis with an exponential function within an absorbing upper boundary layer. Smoothing and filtering are increased gradually from the bottom of the absorbing layer to the model top. Only the temperature field is subject to the nudging condition; winds are not nudged, but allowed to adjust freely according to the model physics and dynamics. The new scheme was tested, along with seven other upper boundary condition schemes, on an intense cyclone event over Marie Byrd Land and Siple Coast, West Antarctica, during the period of 9-14 October 1995. The performance of the various schemes is assessed by verifying model results against temperature soundings obtained from the Global Positioning System / Meteorology (GPS/MET) experiment (Ware et al. 1996).

The eight schemes are shown in Table 1, with the numerical value for the sigma levels in each run. The model top is set at 100 hPa for the first three experiments and 10 hPa for the remaining five. In standard MM5, the truncated wavenumber for the radiative boundary condition is 6. In Exp. Wave3 the truncated wavenumber for the radiative boundary condition is 3. The procedure used in Exp. Asm is a simple filtering (e.g., four-point smoothing) with gradually decreasing strength from full strength at the top to no smoothing at level six. Damping is applied to the temperature, wind and specific humidity fields. A Rayleigh frictional term is added to the momentum equations in the upper five model layers in Exp. Afri, and the frictional coefficient increases with height. In Exp. Nudge, the relaxation lateral boundary condition proposed by Davies and Turner (1977) is revised to serve as an upper boundary condition. Basically, the damping factor for the three absorbing upper boundary conditions increases from the bottom of the absorbing layer to the model top. However, the nudging upper boundary condition provides the most gradual transition for this damping factor.

Table 1. Eight experiments with different upper boundary treatments

Experiment	Upper Boundary Condition	Model Top (hPa)	Description
Control	radiative	100	truncated WN=6
Wave3	radiative	100	truncated WN=3
Lid	rigid lid	100	
Rad10	radiative	10	truncated WN=6
Lid10	rigid lid	10	
Asm	absorbing	10	smoothing u,v,t,q for top 5 layers
Afri	absorbing	10	Adding rayleigh friction for top 5 layers
Nudge	nudging	10	exponential function for top 8 layers

Three 48-hour forecast experiments have been carried out. The Polar MM5 was driven by the NCEP Aviation Model (AVN). Unfortunately there is no AVN archive for the period of our simulation (9-14 October 1995), so the forecast period was selected randomly based on availability. It starts at 0000UTC 3 January 2002. In these three forecast experiments, the model top is set at 10 hPa and the radiative, rigid lid and nudging upper boundary conditions are applied

respectively. European Centre for Medium-Range Weather Forecasts (ECMWF)/Tropical Ocean - Global Atmosphere (TOGA) analysis data are used to verify these experiments. Furthermore, because accurate temperature information can be determined from GPS/MET radio occultations over regions where moisture is negligible, GPS/MET-derived temperature soundings are uniquely suitable for model verification in the upper atmosphere over the Antarctic.

A warm bias is found for most of the experiments compared with the GPS/MET temperature sounding above 9km, except for the Nudging Experiment (Wei et al. 2004). The temperature bias in Experiment Nudge is generally less than 2°C for the layers above 13km, while it is much larger for all other experiments. Even with the model top raised to 10 hPa, the model still generates large warm biases near the model top over those areas where strong vertically propagating waves are expected.

Analysis of the 6-day mean wind velocity at 200 hPa indicates that the control run underestimates the magnitude of the upper level jet by as much as 10 m s⁻¹. This is due to a significantly weakened meridional temperature gradient. Figure 15 shows a vertical cross-sections stretching west to east from the Pacific Ocean, across the northern Antarctic Peninsula, the Weddell Sea, part of East Antarctica, and finally to the Indian Ocean. The slightly elevated surface over the Antarctic Peninsula (near 65°S) and the much higher elevated surface over East Antarctica (from 28°W to 54°E) can be seen in Fig. 15. The cross sections show the wind speed

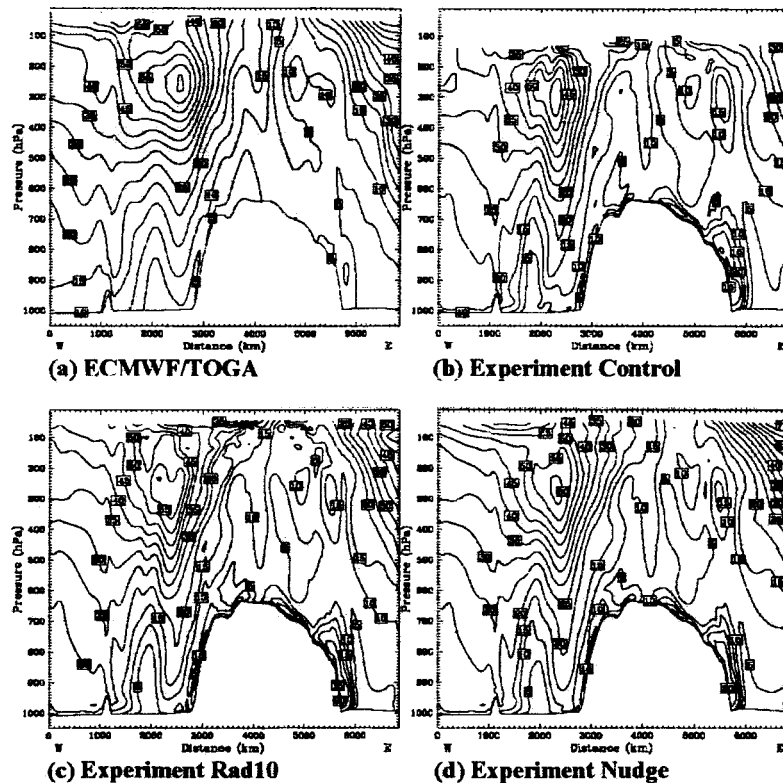


Figure 15. Vertical cross-sections of wind speed (m s⁻¹) at 000 UTC 9 October 1995 for (a) the ECMWF/TOGA analysis, and the Polar MM5 simulations known as (b) Control, (c) Experiment Rad10, and (d) Experiment Nudge. Contour interval is 5 m s⁻¹. The west edge is over the Pacific Ocean, and the east edge is over the Atlantic Ocean. The surface is slightly elevated over the very narrow Antarctic Peninsula and highly elevated over the large East Antarctic land mass.

at 0000 UTC 9 October 1995. The location of the upper level jet (Polar front jet stream) is near 250 hPa in the ECMWF/TOGA analysis (Fig. 15a), while it is simulated 50 hPa lower in the control run (Fig. 15b), and the magnitude is 5 to 10 m s^{-1} weaker than the ECMWF/TOGA analysis. With the model top raised, the upper level jet moves up as well (Figs. 15c and 15d). Both Experiment Rad10 and Experiment Nudge simulate the correct location of the jet, but the magnitude in Experiment Nudge is closer to the ECMWF/TOGA analysis.

The case study from October 1995 indicates that the nudging upper boundary condition may provide an important enhancement to simulations over Antarctica. It is necessary, however, to statistically evaluate the nudging upper boundary condition over a more extensive period for which a broad range of synoptic conditions occurred. Therefore, forecasts from winter 2002 (before the new condition was applied) and winter 2003 (after the change) are compared to quantify the impact. The comparison is done for an AMPS domain with 30-km resolution. Fortunately, JJA 2002 and JJA 2003 were climatically similar (Wei et al. 2004), thus allowing for a valid comparison.

The data from the AMPS Polar MM5 are statistically evaluated against surface and radiosonde observations. They are compiled from 3-hourly and 6-hourly surface data and 12-hourly radiosonde data. The statistics presented are bias (model minus observed), normalized root mean square error (NRMSE), and correlation coefficient. The NRMSE is the ratio of the RMSE to the standard deviation of the observations; this allows the RMSE to be compared between sites with different variability. Correlation coefficients were tested for significance from zero at the 99% confidence level, and in nearly every case passed. The methods are described further in Bromwich et al. (2004b).

Figure 16 (next page) compares the spatial distribution of the correlation, bias, and NRMSE of AMPS POLAR MM5 versus observations for variables at selected upper air and surface stations for JJA 2002 (Fig. 16a, left hand side) with JJA 2003 (Fig. 16b, right hand side) for 150-hPa temperature and wind speed, and surface pressure for all 36-60 h forecasts at 12 hour intervals. Large improvements in the 150-hPa fields are apparent, with higher correlation coefficients at almost all stations, and lower biases and NRMSEs at nearly every station in 2003. This indicates the satisfactory skill of the GFS upper-level temperature fields, which are used to nudge the AMPS forecasts. Noteworthy changes are also observed for surface pressure. Correlation coefficients and NRMSEs improve at nearly all of the stations (Wei et al. 2004). Furthermore, the vertical distribution of the atmospheric fields indicate that the effect of the nudging upper boundary condition extends down to the earth's surface.

In summary, the Davies relaxation boundary condition has been revised and applied to the upper boundary (called the nudging upper boundary condition). It is found that the nudging scheme is effective in damping out the waves and in providing a better fit to the verifying soundings. This is confirmed for simulations driven by not only analysis data but also global model forecast output. The nudging upper boundary condition used in this study also effectively removes the two-delta vertical waves generated by using sigma coordinates above steep terrain.

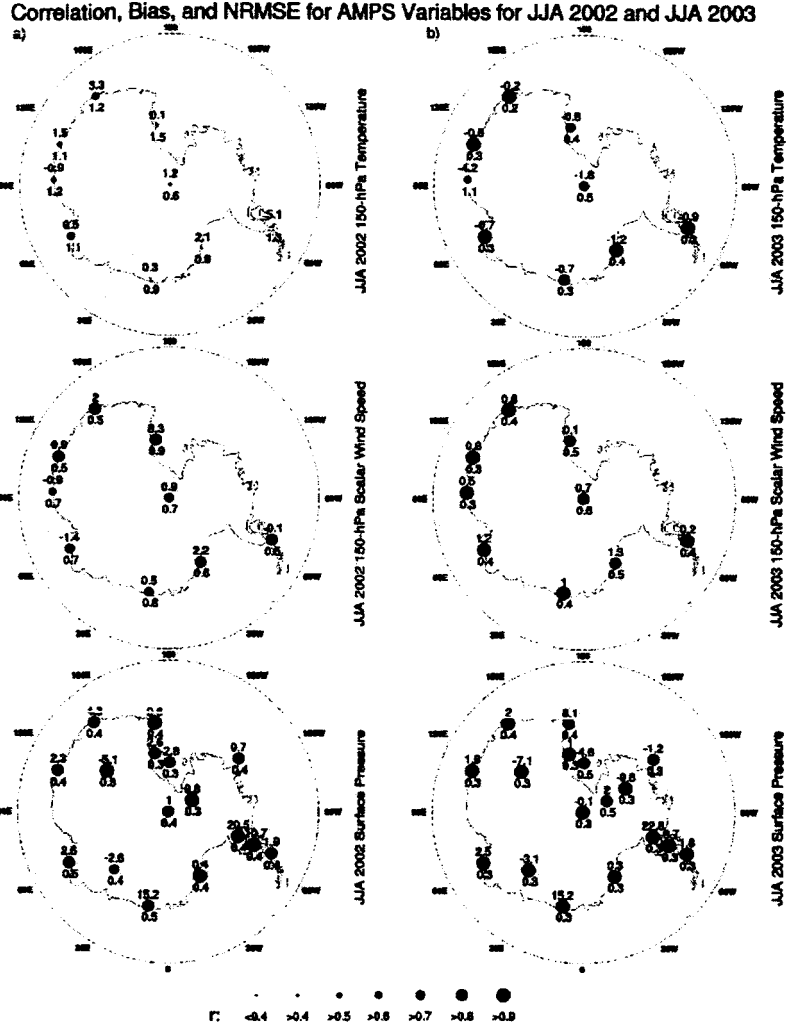


Figure 16. Correlation coefficient (dot size) bias (top number; units given below), and NRMSE error (bottom number; dimensionless) at selected Antarctic stations for 150-hPa temperature, 150-hPa scalar wind speed, and surface pressure for (a) JJA 2002 (plots on left hand side) and (b) JJA 2003 (plots on right hand side). The statistics are calculated for hour 36-60 for all 0000 UTC AMPS 30-km forecasts for the two periods. Bias and RMS error units are $^{\circ}\text{C}$, m s^{-1} , and hPa for temperature, winds, and surface pressure, respectively.

5. Climatic Simulation (OSU/BPRC)

The ability of Polar MM5 to capture the climate variability of Antarctica is evaluated by a simulation of the El Niño-Southern Oscillation (ENSO) cycle during the period July 1996-June 1999 (Bromwich et al. 2004a). The simulation provides a more comprehensive assessment of the ENSO variability than can be achieved with observational datasets. Largest ENSO response in the Polar MM5 simulations is located over the Ross Ice Shelf-Marie Byrd Land and over the Weddell Sea-Ronne/Filchner Ice Shelf. The simulation confirms the Antarctic Dipole (Yuan and Martinson 2001) as surface temperature, meridional winds, precipitation and cloud fraction

exhibit anomalies of opposite sign between the Ross Ice Shelf/Marie Byrd Land and over the the Weddell Sea-Ronne/Filchner Ice Shelf. When comparing the El Niño / La Niña phases of this late 1990s ENSO cycle, the circulation anomalies are nearly mirror images over the entire Antarctic, indicating their significant modulation by ENSO. Large temperature anomalies, especially in autumn, are prominent over the major ice shelves. The Polar MM5 simulations are in broad agreement with observational data, and that the simulated precipitation closely follows the ECMWF TOGA precipitation trends over the study period. In summary, the 1996-1999 ENSO-cycle simulation suggests that the Polar MM5 is capturing ENSO-related weather variability with good skill and may be a useful tool for future climate studies.

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